PRINCIPLES OF THE INFORMATION THEORY
OF VISIBILITY IN THE ATMOSPHERE,
Chapter Titles and Introduction.

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[TRANSLATION]

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Principles of the Information Theory
of Visibility in the Atmosphere
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Introduction

Visibility in the atmosphere naturally means visibility against the background of the sky, and this in turn means distinguishing the total radiation of a body and the glare from the radiation of the sky. If, in this situation, it is sufficient to establish the presence of radiation not originating in the sky, then we have a problem in observation. If, in addition, it is necessary to discern certain signs on the observed body, we are faced with a problem in discrimination. This latter and more complex problem in principle reduces to the former, since discrimination requires only the simultaneous observation of a certain number of elements for establishing the presence of the distinguishing sign which is of interest.

In this connection, the term simultaneous requires clearer definition. No experiment enables one to establish simultaneity with absolute accuracy. Observation implies some change in the state of the detector, as a result of action of the radiation. This change may be preserved (that is, the detector may have memory) for a period, or it may not be preserved, but in any case some finite period of time is required in order for it to arise and to be utilized. The results of the action of light signals separated by intervals smaller than the time of inertia will pile up upon one another, and as far as the detector is concerned all such signals will be simultaneous.

The possibility of observation is defined by the radiation from the body being observed, the background radiation, and the characteristics of

the radiation detector being used in the observation. In principle, however, there are still other limitations, derived from the fact that the radiation fluxes being compared fluctuate.

In modern atmospheric optics we distinguish a broad class of important problems in which one has to cope with the fact that the role of statistical fluctuations of luminous fluxes, or of the secondary signals within the detector which result from them, is a substantial one. I refer, first of all, to problems associated with the observation of a body of small angular dimensions (for example, as in the case of astronavigational and other special tasks), and in addition to all cases whatever which involve the use of the human eye. Here the point is that visual perception is the result of the absorption of photons by the molocules of the light-sensitive tissue of the retina, and that the probability of observation is circumscribed by the random statistical fluctuations in a random quantity whose mathematical expectation is proportional to the brightness of the light stimulus. This quantity is called "the number of effectively absorbed quanta".

Beginning with 1933, S. I. Vavilov and his students made a number of studies (the results are summarized in [1, 2]) in which it was demonstrated experimentally that

1) if the observer is presented with a series of brief flashes of identical brilliance and duration, then the number of effectively absorbed quanta during the time of a single flash is a random quantity distributed according to Poisson's law; and

2) the observer will see the test only if the number of

quanta does not fall below a certain threshold value.

Obviously, statements of this sort are applicable not only to the

eye but to any visual structure, since vision is in any case the result of

the absorption of light quanta.

If the action of a constant field of radiation is describable in

terms of a steady-state Poisson process, then the problem of observation

can be formulated mathematically as a problem of distinguishing the para-

meters of two Poisson distributions. Thus, as S. I. Vavilov has pointed

out, a theory of vision (and particularly visibility in the atmosphere)

must be based on the theory of probability, and must proceed from the sta-

tistical properties of the background radiation and the radiation of the

observed body.

The radiation of the sky is characterized perfectly by the density

of the luminous flux, which is known for every element of the celestial

sphere.

We shall not concern ourselves here with solar radiation, since ob-

servation against the background of the solar disk is not a very likely

phenomenon. Scattered radiation is determined by the position of the sun,

the state of the atmosphere, and the reflective properties of the underlying

surface. All of these factors vary with time, but the amount of variation

occurring during a single observation is usually so small as to be negligble.

Therefore, we shall consider the field of radiation to be steady-state in

character.

In many situations it is necessary to take into account the time characteristics of the detector. If the object observed is moving rapidly, the problem is complicated in that the brightness of individual portions of the sky may differ by as much as several powers of 10, while rapid variation of the coordinates signifies, therefore, a rapid variation in the background radiation.

It is important to emphasize that no matter what are the practical difficulties of the experimental or mathematical methods employed in determining the spectral density of the sky radiation, the latter is a fixed quantity. On the other hand, the radiation spectrum of the body observed and the characteristics of the receiver are, in principle, quite arbitrary. The capabilities of the detector are limited by fluctuations of the signal and by the presence of noise. It is therefore natural to pose the problem of determining the conditions under which a body can be observed against a given background with a given probability. After formulating this general problem, our next concern will usually be to consider radiation in the visible spectrum and to make the appropriate calculations for a detector with a spectral sensitivity factor falling on the relative visibility curve of the average human eye. Quite apart from the practical importance of visual observations, this limitation leads to the natural assumption that the eye in its course of prolonged evolutionary improvement, has achieved the characteristics which are optimal for the tasks imposed upon it. Actually.

comparison with the eye may lead to ideas which will be useful in developing radiation detectors. The use of these general methods, moreover, will not lead to any essentially new difficulties in the analysis and evaluation of detectors with different characteristics.

It can be assumed beforehand that the conditions of observation must be expressed by a certain functional of the link between (1) the radiation characteristics of the body and the background, (2) the angular dimensions of the body, (3) the observation time, and (4) the probability of observation. In this sense the conditions of observation are identical with the threshold conditions of vision, which have been treated extensively in the literature of physiological optics (for a survey of these works we suggest V. V. Meshkov's book [3]). Therefore, any general theoretical study of the problem should reveal the basis of certain empirical laws of the functioning of the eye. Correlation with the firmly established fact of the biophysics of vision represents a serious experimental verification of theory.

From what has been said it is evident that the problem of visibility in the atmosphere which we are considering calls for the enlistment of the concepts, methods and achievements of such differing sciences as atmospheric optics, the theory of information, the statistical theory of observation, bionics, and the biophysics of vision.

By reviewing the threshold conditions of vision from the general positions of the theory of information, one can formulate criteria which

must be satisfied by an optimal characteristic of the detector. In any specific case, the problem naturally reduces to three stages:

1) determination of the field of radiation, and calculation of the reduced fluxes from the elements of the celestial sphere;

2) derivation of the threshold conditions of observation for the particular functional scheme of the detector; and

3) comparison of the radiation of the body with the combined radiation of body and haze, and construction of a working characteristic of the detector which will connect the signal power with the probabilities of observation and of "false alarms".

Chapter 1 is devoted to the general theory. As an initial physical presumption we adopt the concept of radiation, and of the steady-state Poisson process, and then derive its justification and the basic consequences--addition of intensities of radiation fluxes, the weakening of those fluxes through the absorbing layer, Bouguer's law, and the equation of transfer (Section 1). In Section 2 we formulate certain general properties of the class of detectors under study, and establish the conditions under which a detector can be characterized by the spectral sensitivity curve. In Section 3 we describe the construction of a system of light units, and compute the coefficient uniting the light units with the photon number. In Sections 4 and 5 we formulate criteria for an optimal characteristic of a detector--namely the principle of constancy of the threshold

of information, and the principle of the energy minimum of uninterrupted

signal. Here we set forth the conditions under which visibility is deter-

mined by contrast, and supply a mathematical formulation of physical dis-

continuity in terms of information theory. One point of interest is that

the formula expressing the principle of energy minimum follows from the

assumption of the high contrast sensitivity of the receiver. Finally, in

Section 6 we discuss the limitations imposed on the structure of the sensor

by the visual apparatus itself, which is intended for the observation of

bodies of small angular dimensions.

Chapter 2 is a brief survey of the basic facts of visual biophysics,

and a comparison of those facts with the theoretical formulations arrived

at in Chapter 1. The basic empirical laws establishing a scale of various

brightnesses (Weber's law), and the connection between the threshold values

of brightness and the duration of light stimulus (the Blondel-Rey law),

signify that the eye in fact illustrates the principles of optimal recep-

tion information as formulated in Chapter 1. Data on the structure of the

retina confirm the conclusions of Section 6, Chapter 1, regarding the

structure of a sensor.

Chapter 2, in addition, includes the formulation of general prin-

ciples which will be found useful in the resolution of specific problems

in developing visual systems.

Chapter 3 is a discussion of background radiation--the field of

shortwave radiation. In this chapter we take up the methods and results

of only the most recent studies in this field, conducted after the publication of two fairly extensive monographs by one of the present writers. Chapter 3 can therefore be considered as a supplement to those monographs. Since experimental data in this area are still very fragmentary, we have included in the chapter the method used by K. S. Shifrin and I. N. Minin for calculating the brightness distribution of a cloudless sky, along with tables for such calculation. It is observed that the Shifrin-Minin method has thus far not been discussed in the monographical literature.

In Chapter 4 are given examples of the derivation of visual threshold conditions, and of calculation of the working characteristics of radiation detectors. Functional schemes for the detectors are chosen to correspond with the various laws of vision, whether determined empirically or on the basic of theoretical considerations. The discovery of the theoretical possibilities opened up by the use of every such law is of great importance in the rational selection of designs for detectors.